Scientific Council
June 27th, 2023

The Belle II vertex detector upgrade proposal

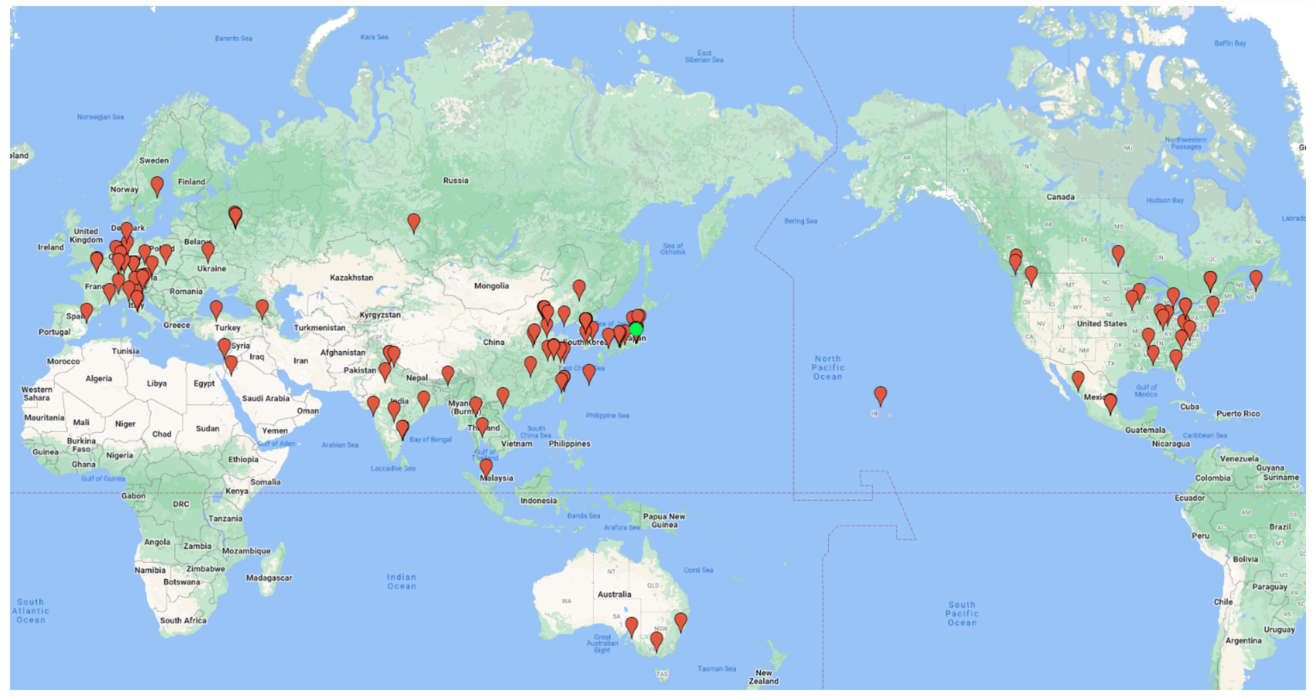
On behalf of the Belle2-IPHC group

- The Belle II experiment in a nutshell
- Rationale for a vertex detector upgrade
- Project overview and longer term R&D
- Requested support from C4Pi

Belle II in a nutshell

Belle II at SuperKEKB: a Super-b-c-τ Factory

- Search for new physics with precise measurements in b-c-τ sector.
  - Unique skills: final states involving neutrals, V0 and missing energy, and inclusive measurements.
  - Belle II physics book PTEP 12 (2019) 123C01.
  - Update: Snowmass white paper arXiv 2207.06307.

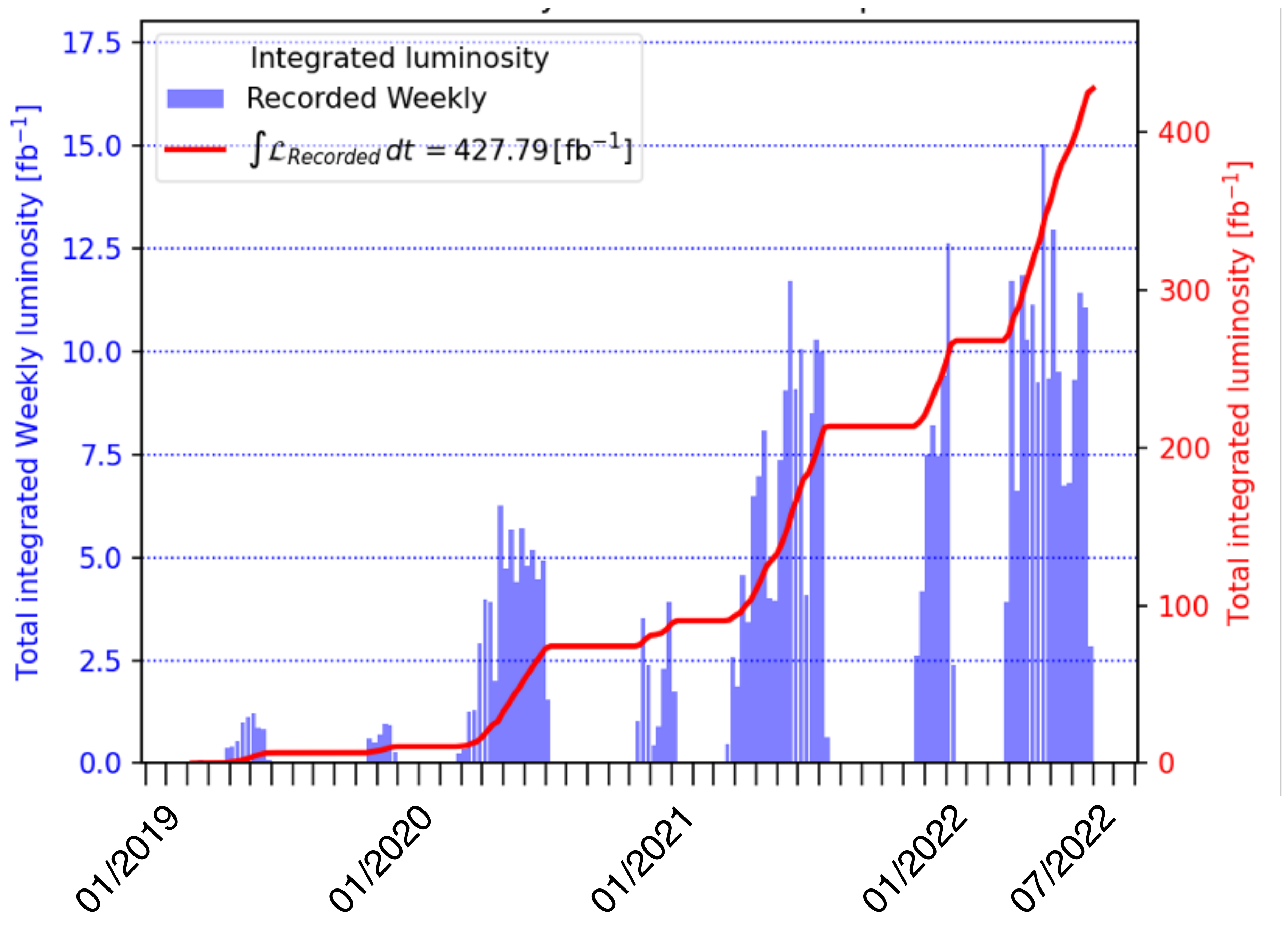



Belle II collaboration: ~1000 researchers, 26 countries

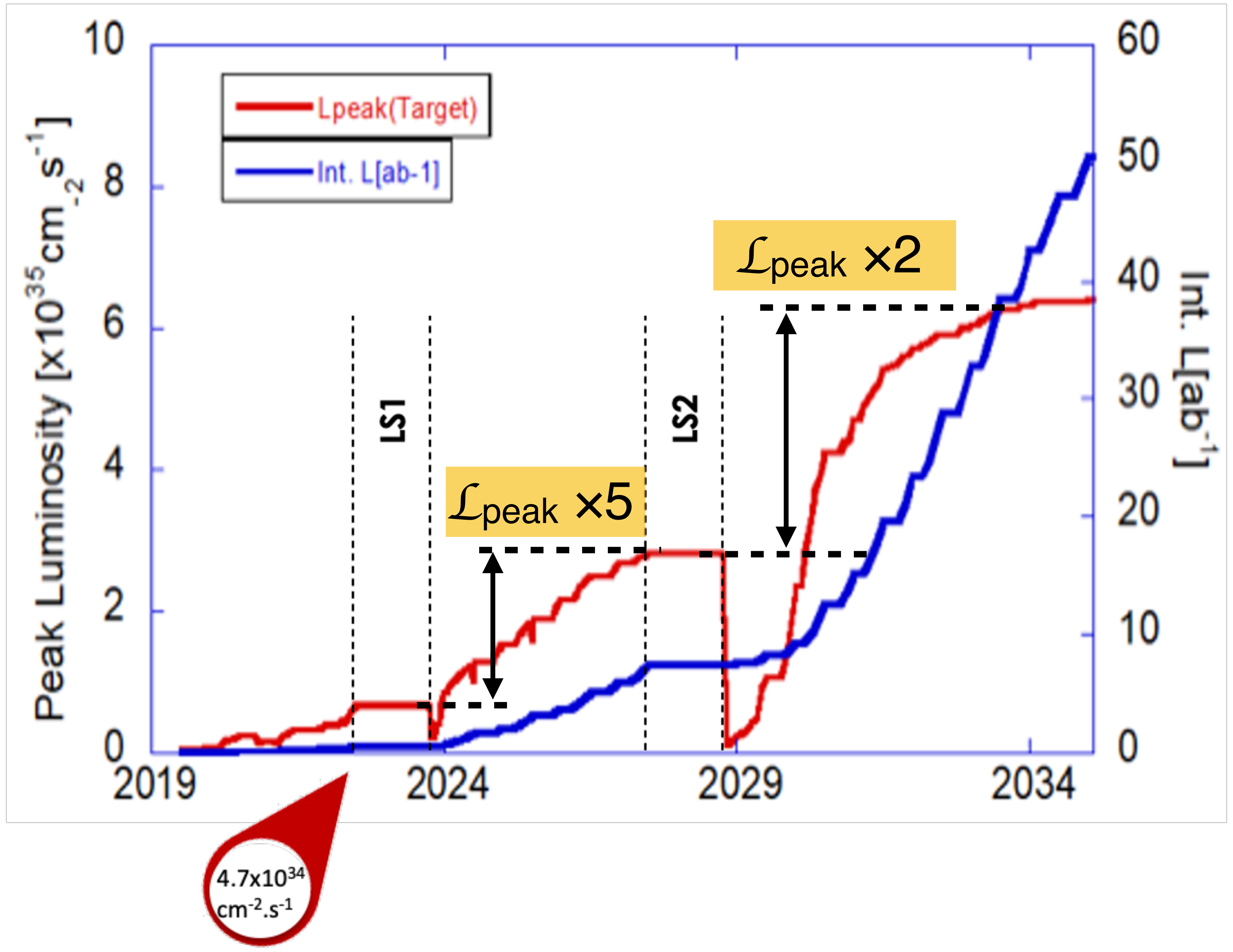
- Built up on Belle (& BaBar) success.
  - The physics of the B Factories Eur.Phys.J.C 74 (2014) 3026.
- New machine: SuperKEKB.
  - $e^+ e^-$ asymmetric collisions around Y(4S).
  - Nano-beam scheme.
  - Targets Intensity Frontier: $\mathcal{L}_{peak} \sim 6 \times 10^{35}$ cm^{-2} s^{-1}.

Belle II delivering physics results

- Physics started in 2019.
- World record peak luminosity: 4.7×10^{35} cm^{-2} s^{-1}.
- First Long Shutdown: July 2022 - Dec 2023:
  - Completion of pixel detector, replacement of TOP PMT.
- Integrated luminosity so far: 428 fb^{-1} ~ BaBar.
- Already a key player in the flavour landscape:
  - >30 major publications: e.g., $B \to K \nu \nu$, $B \to X_s l \nu$, …
    e.g., 13 talks with 2023 new results at FPCP 2023.
  - Contribution from Belle2-IPHC (4 permanent researchers, 2.5 postdocs, 2 PhD students):
    - Measurement of beam induced background with a CMOS detector, designed, built, installed and operated, during commissioning. NIM A 967 (2020) 163862 & NIM A 1040 (2022) 167168.
    - Operation of the silicon strip vertex detector.
    - Physics analyses: search for $B \to K \nu \nu$, TDCP asymmetry of $B \to K^0_S \pi^+ \pi^- \gamma$, developments of key algorithms.



Belle II experiment prospects



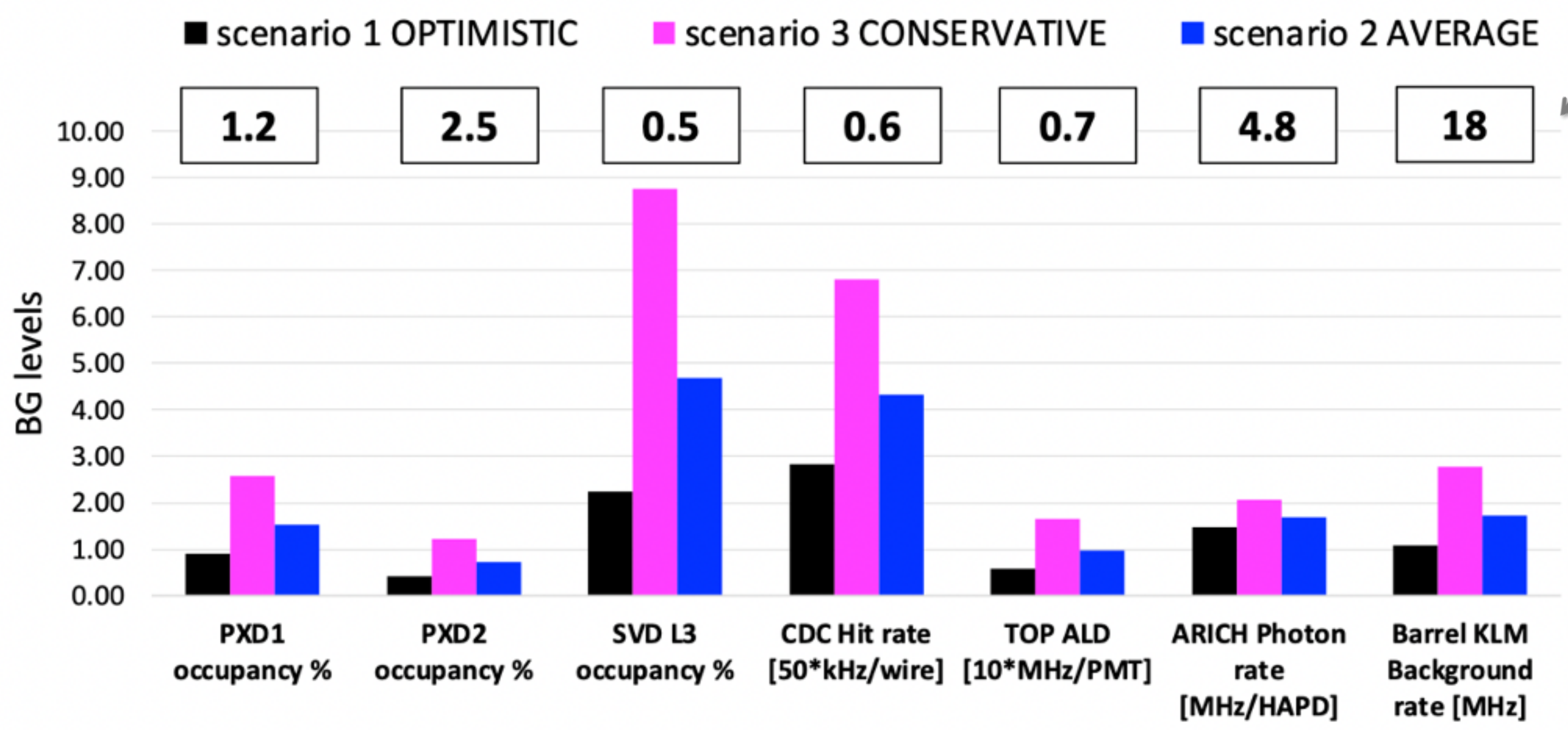
- **Increase the luminosity:**
  - **Short term**: SuperKEKB improvements in LS1.
    - $1 \times 10^{35} < \mathcal{L}_{peak} < 2.8 \times 10^{35}$ cm^{-2} s^{-1}.
    - Mitigate different machine induced background sources.
  - **Mid-term**: SuperKEKB upgrade in LS2 (~2027) → detector upgrade also.
    - $\mathcal{L}_{peak} \rightarrow 6 \times 10^{35}$ cm^{-2} s^{-1}.
    - Significant modification of Interaction Region.
    - Impact on detector performance.
  - **Long-term**: LS3?
- **Get more physics per ab^{-1}:**
  - Increased luminosity ⊗ upgraded detector ⊗ improved algos.
  - Consider polarised e^+ beam.

➛ Snowmass Whitepaper: The Belle II Detector Upgrade Program, arXiv:2203.11349.

Rationale for a vertex detector upgrade

Increased machine induced background

- Extrapolation of machine induced background suffers from large uncertainty.
- Most impacted detectors: silicon vertex detector, central drift chamber, time of propagation.
  ➛ VTX upgrade with increased granularity of vertex detector improves tracking robustness.



$$\text{safety factor} = \frac{\text{detector limit}}{\text{background rate}}$$

(for conservative scenario)

Extrapolation at $\mathcal{L}_{peak} = 6 \times 10^{35}\ cm^{-2}\ s^{-1}$

BG hypothesis	Finding efficiency
optimistic sb BG ×2	0.979 / 0.813 0.944
average sb BG ×5	0.974 / 0.781 0.943
conservative sb BG ×10	0.976 / 0.703 0.936

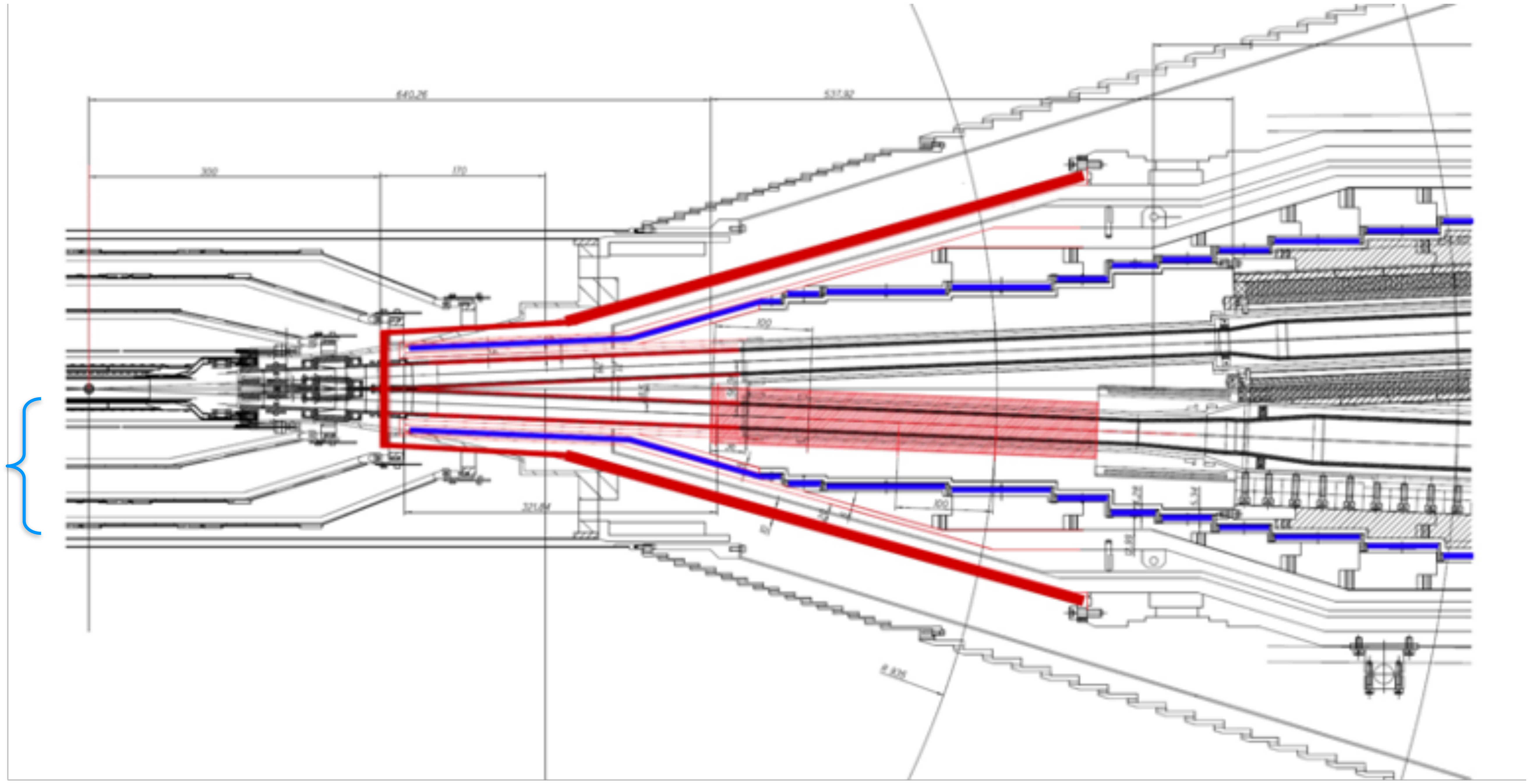
VTX **upgrade** standalone
CDC standalone
Full tracking

Modification of the interaction region

- Considered options to increase luminosity necessitate modification of the Belle II acceptance.
  ➛ vertex detector geometry needs to be adapted during LS2.

Example of interaction region
with new solenoid
(1/2 transverse view)

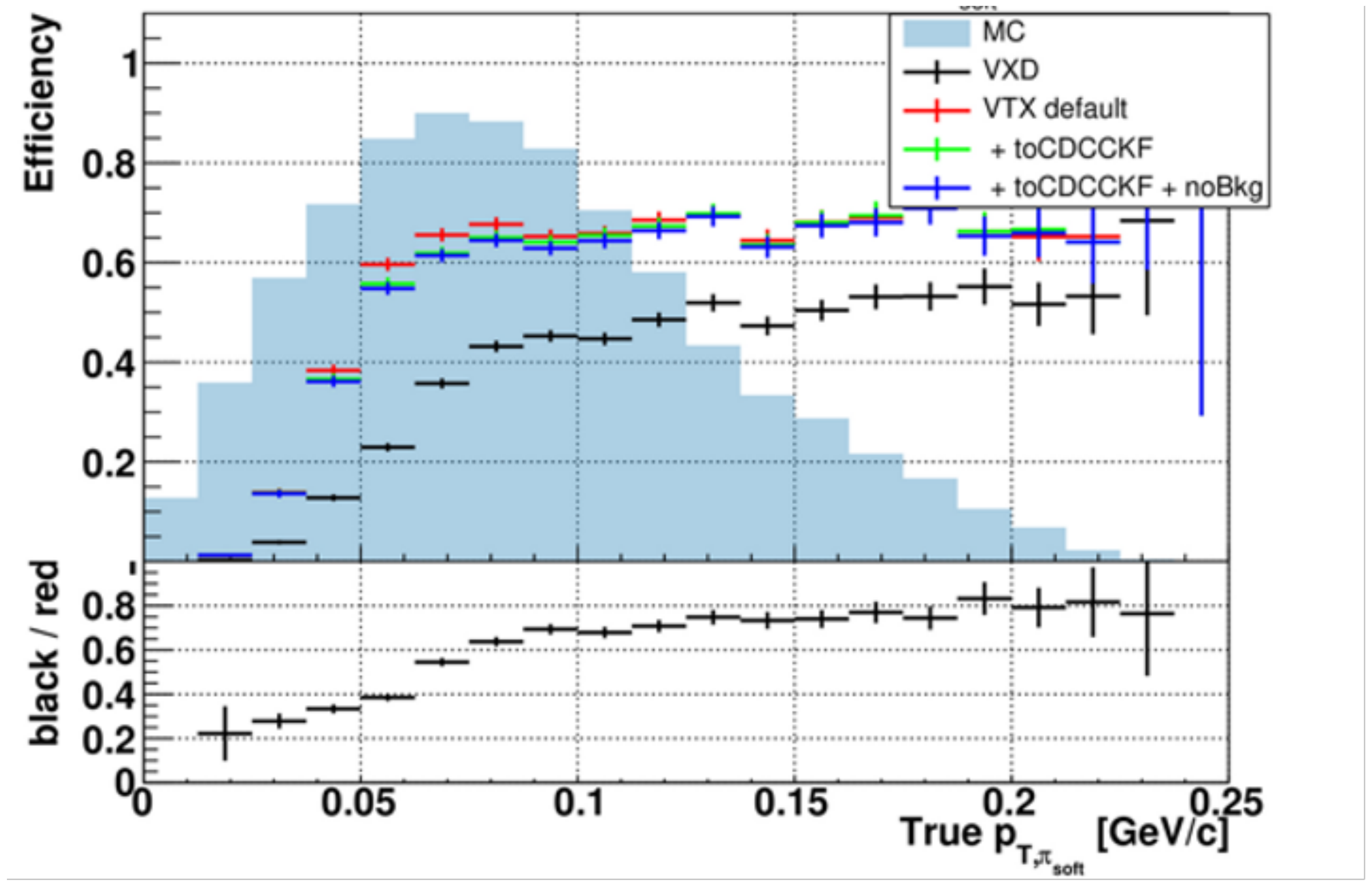
Vertex detector layers



Improved performance for physics

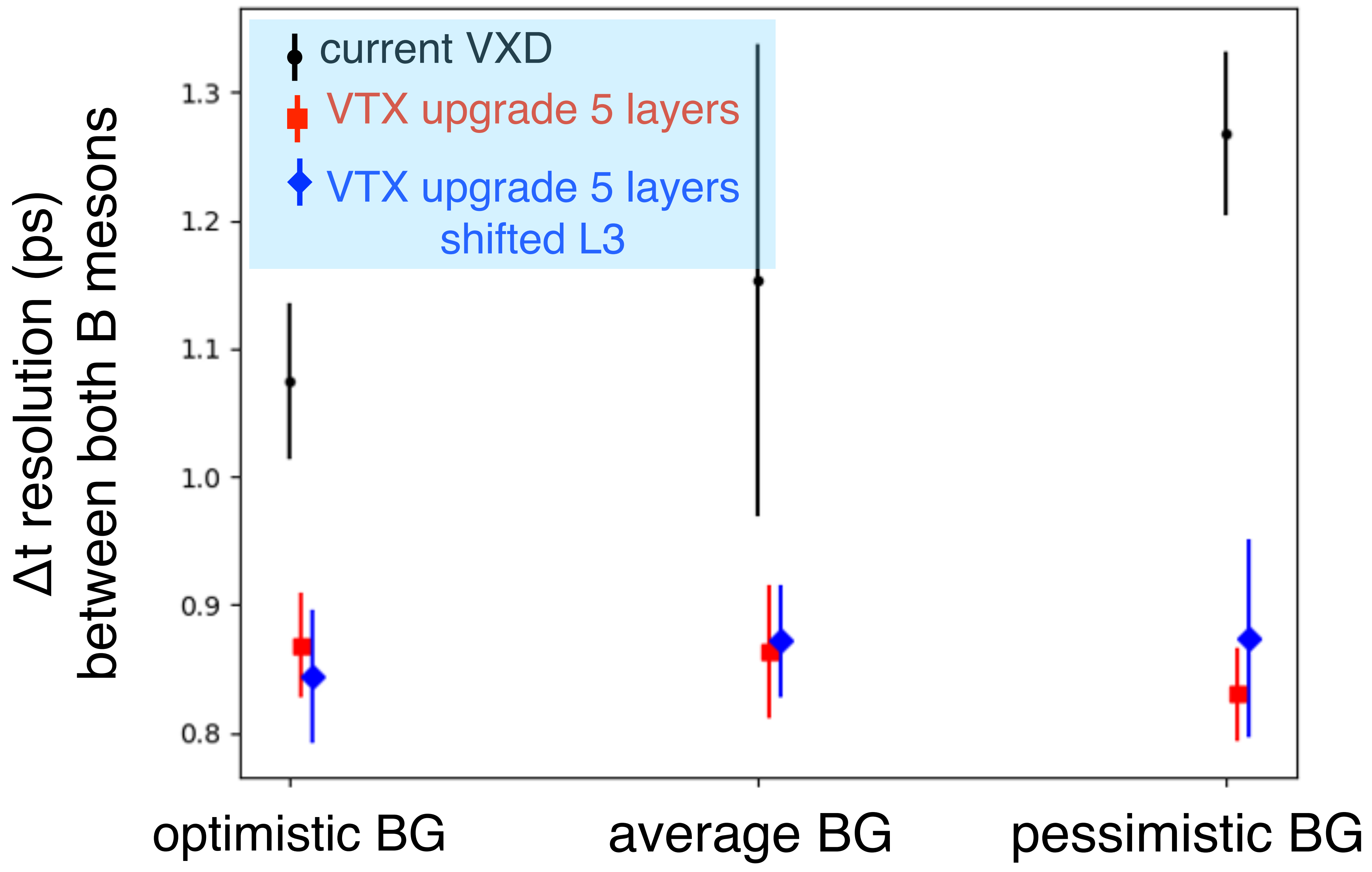
- Low momentum tracking.

  Study of soft π reconstruction from $B^0 \rightarrow D^{*-} \mu^+ \nu$ decays with $D^{*-} \rightarrow D^0 \pi^-$



- Secondary vertex resolution.

  Study of TDCP asymmetry of $B^0 \rightarrow K^0_S \pi^+ \pi^- \gamma$ decays.



➢ Improved performances thanks to lower material budget & higher granularity.

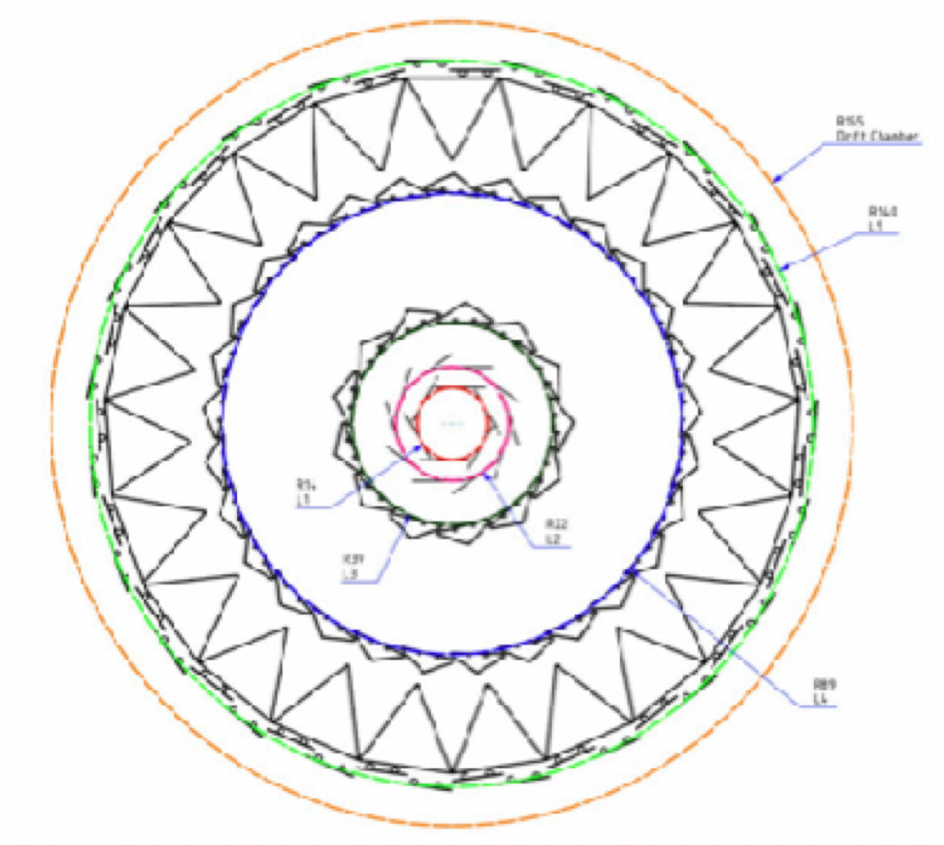
VTX upgrade project for LS2

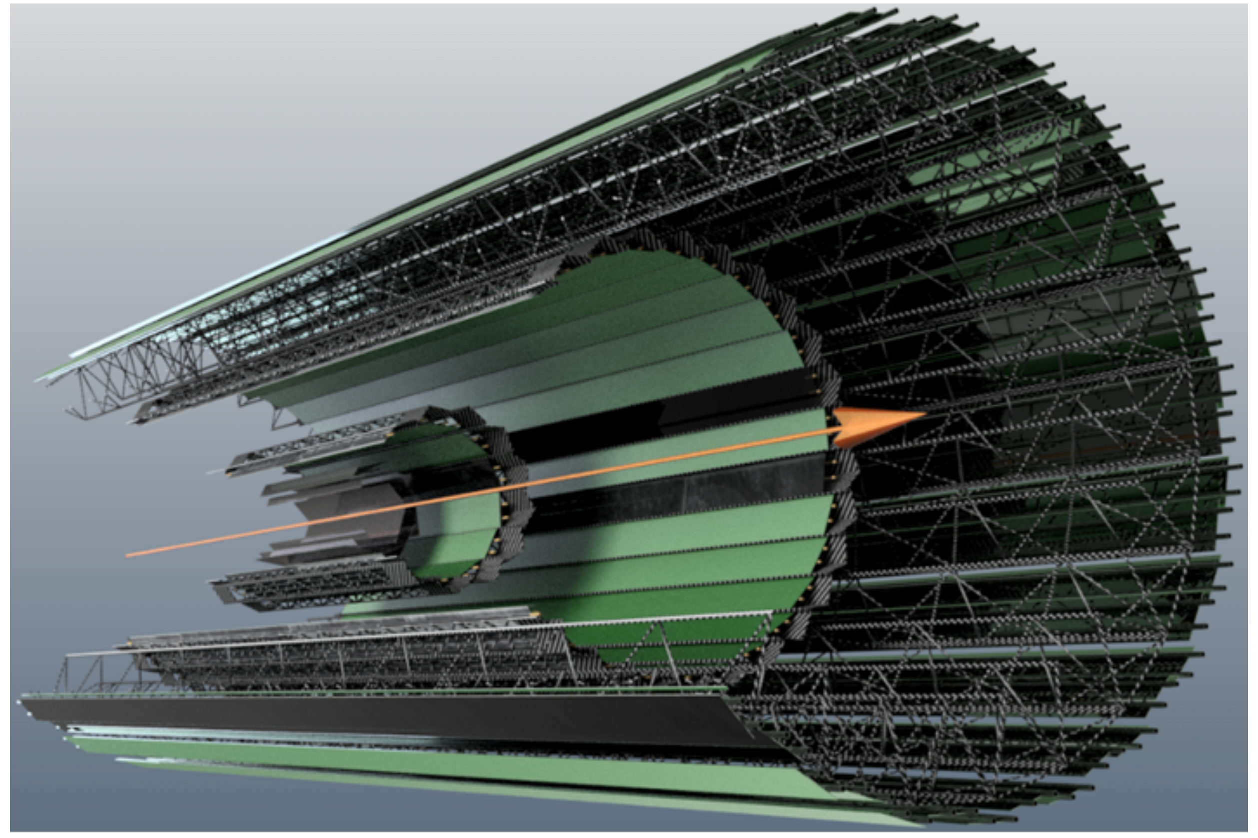
VTX general concept

- 5-layer design:
  - Total surface ~1 m².
  - 1 unique sensor, same granularity: depleted CMOS MAPS (OBELIX).
  - Fast integration time: all layers participate to pattern recognition.
  - Total event size ~30 kBytes to fit HLT constraints.
  - All services on backward side.
  - Inner and outer parts: iVTx and oVTX.
  - Flexible ladder concept to cope with potential modification of interaction region.

➛ « simple, robust, doable »

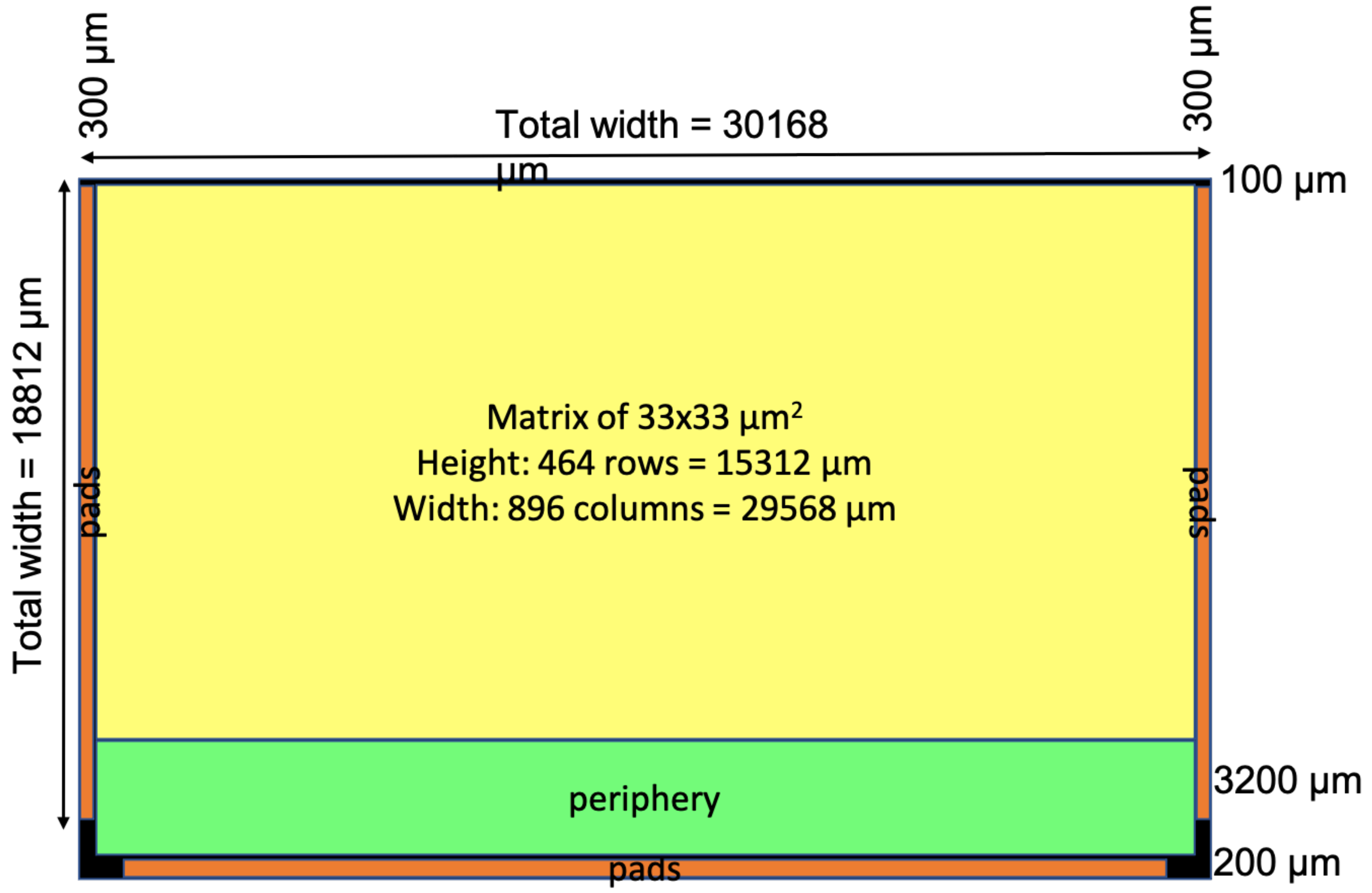
- VTX collaboration:
  - Austria: HEPHY Vienna.
  - France: CPPM, IJCLab, IPHC.
  - Germany: Bonn, Dortmund, Göttingen.
  - Italy: Bergamo, Pavia, Pisa.
  - Japan: KEK Tsukuba.
  - Spain: IFIC (CSIC-UV) Valencia.
  - Under discussion: in Germany, China, UK.



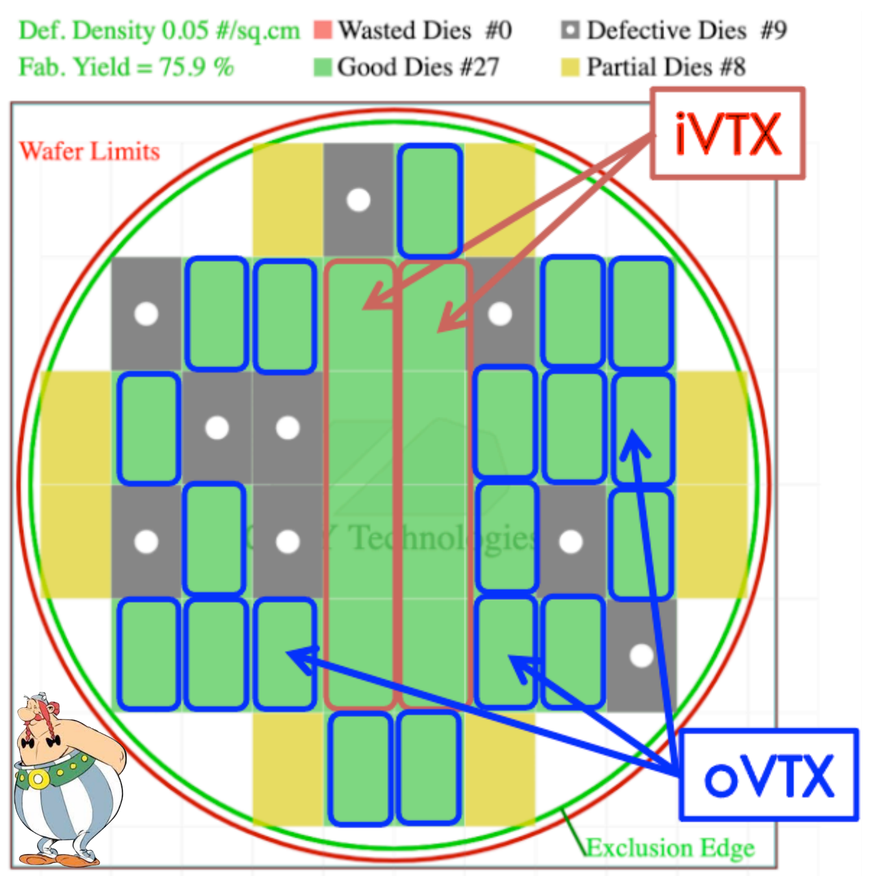


Optimised BELle II piXel sensor

- Pixel matrix: OBELIX, based on 180 nm TJ-Monopix-2.
  - Radiation tolerance granted.
  - Frequency lowered to 10-20 MHz: time-stamp 100-50 ns.
  - Possible power/speed optimisation.
- Power pads:
  - Power regulator added: simplified system integration.
  - Area limited < 150 µm × 18.8 mm.
- Periphery:
  - New end-of column adapted to Belle II trigger.
    - Time-stamped hits stored in memories.
    - Read-out when time-stamp matched with trigger.
  - Single output at 320 MHz: average bandwidth/sensor 140 Mbits/s.
  - RD53 control/readout protocol.
  - Biasing generation and monitoring.



➛ Design progressing for submission end of 2023.

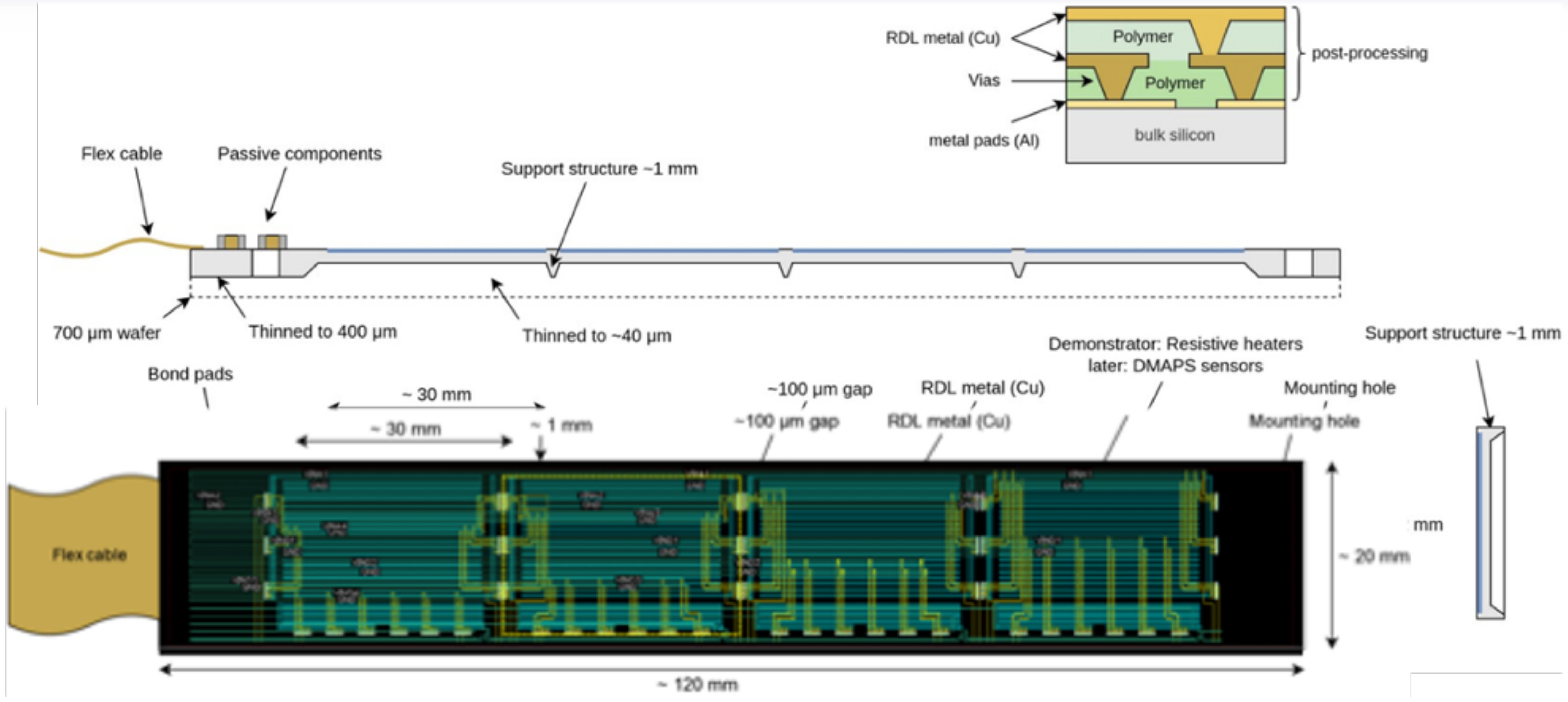


Size optimised to maximise sets of 4 contiguous sensors.

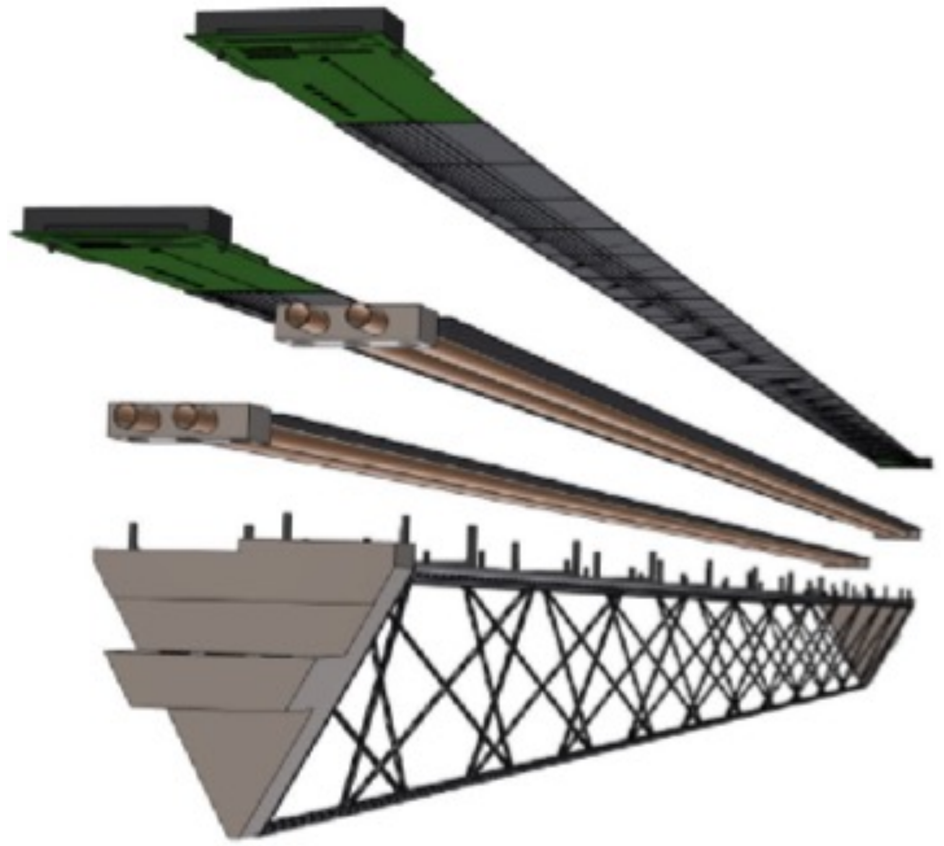
Led by C4Pi for iVTX.

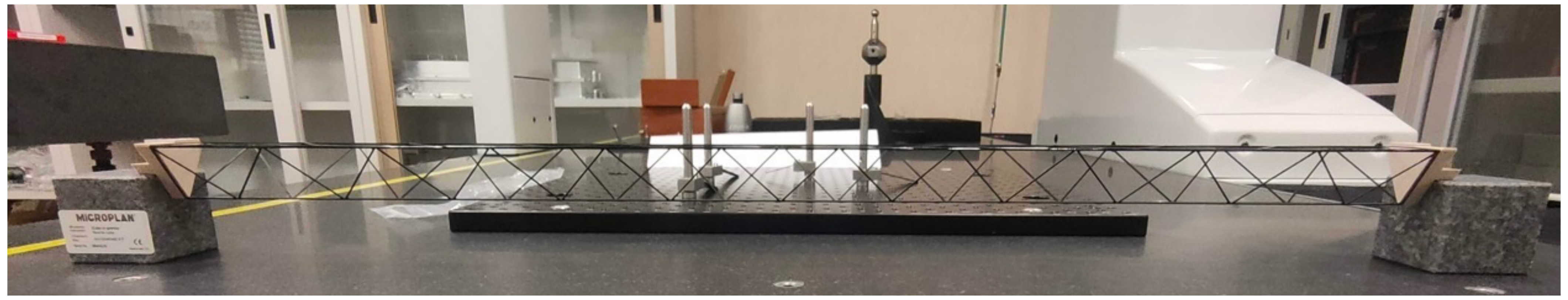
Detection layer concept

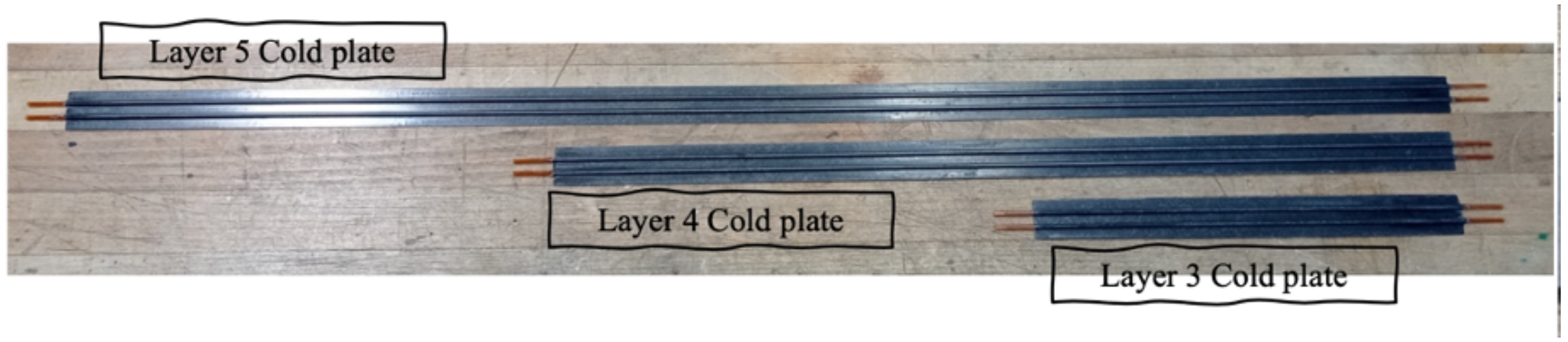
- iVTX All-silicon module: 2 layers at R < 3 cm.
  - < 0.15% X_0/ layer, 12 cm long.
  - 4 contiguous sensors diced as a block from wafer.
  - Additional redistribution layer for interconnection.
  - Heterogeneous thickness (thinness & stiffness).
  - Air cooled.



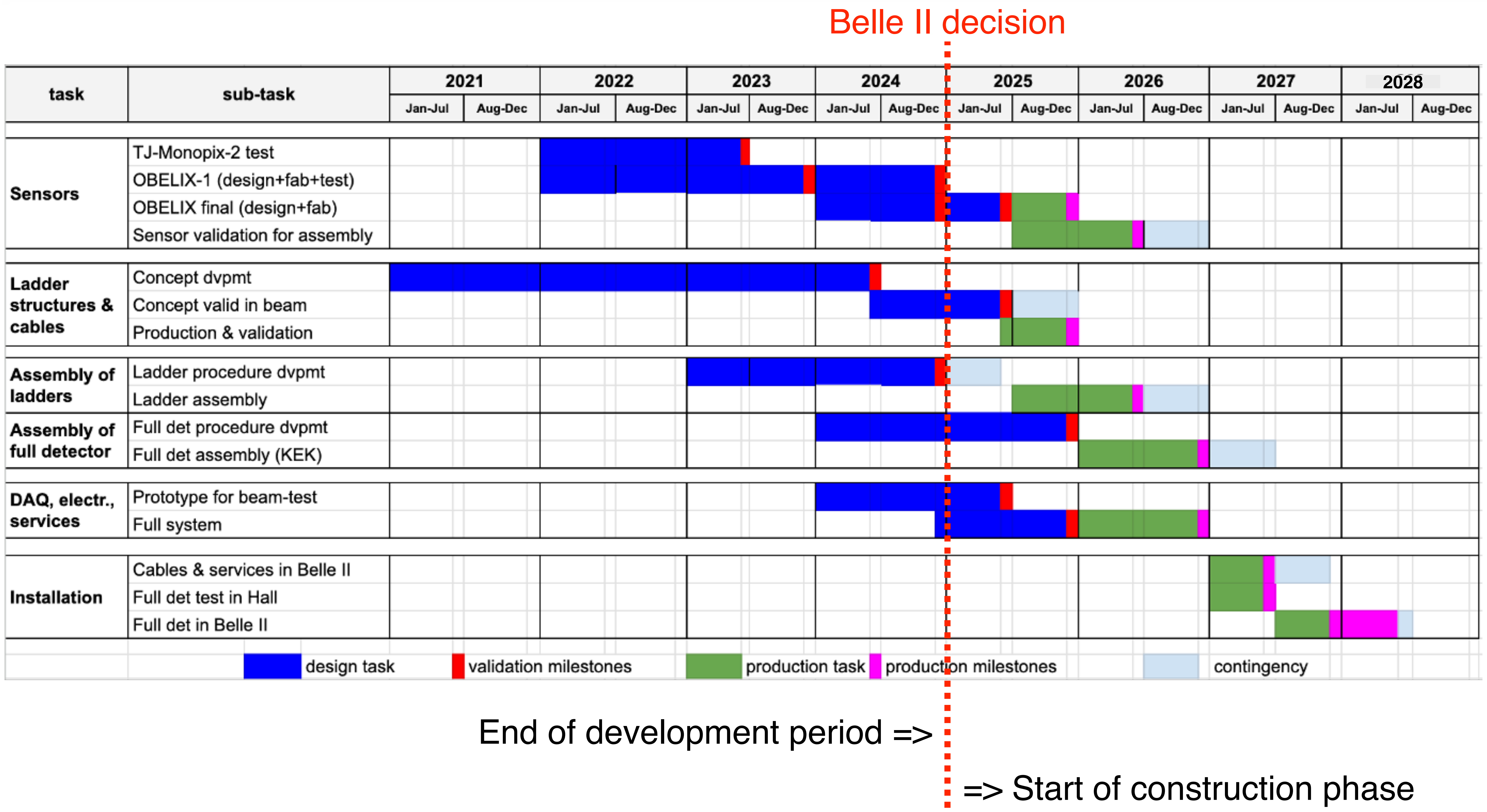
- oVTX long staves: 3 layers at R > 3 cm.
  - Based on ALICE-ITS2 concept.
    - Carbon-fiber truss support frame.
    - Cold-plate with water coolant.
    - Long-flex for power & data.
  - L3-L4, R = 4-9 cm, length 24-45 cm.
    - Single sensor row, ~0.5% X_0/ layer.
  - L5, R = 14 cm, length 70 cm.
    - Double sensor rows, ~ 0.8% X_0/ layer.







VTX schedule



➛ An aggressive chart, set to reach installation in early 2028.

Total surface only ~1 m^2.

- **Assumptions for construction:**

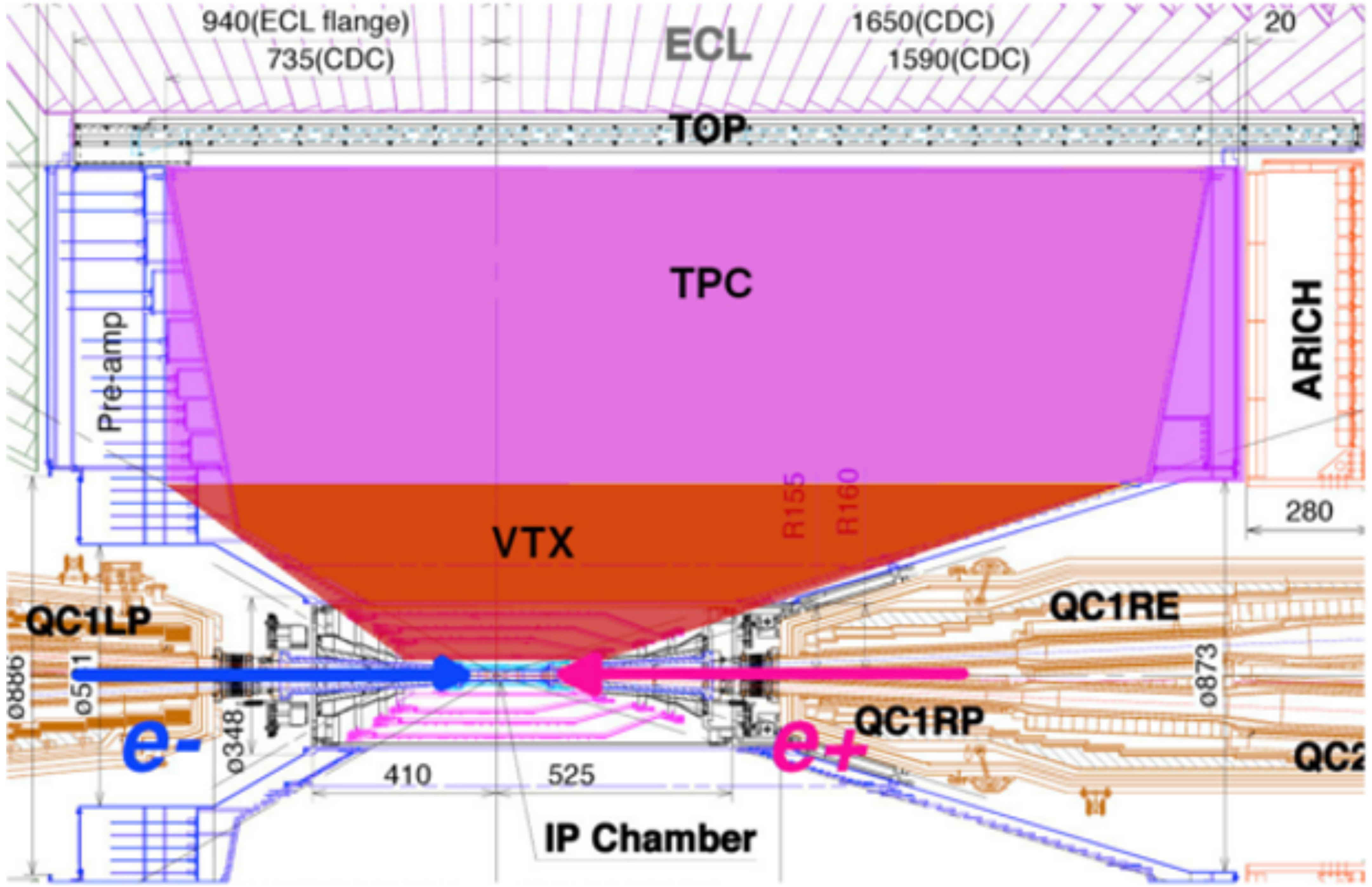
  4 days/week, 3 weeks/month, +15% spares.

  - Wafer probing: 6 months.
    - 140 wafers, 1 wafer/day.
    - 2 sites.
    - Dicing in parallel.
  - iVTX ladders: 10 months.
    - 20 ladders, 2 ladders/month.
    - Only at IZM Berlin.
  - oVTX modules: 8 months.
    - 100 modules, 3 modules/week.
    - 2 sites.
  - oVTX ladders: 10-15 months.
    - 60 ladders, 2 ladders/month.
    - 2-3 sites.

Longer term R&D

Long term upgrade of the central tracker

- Context: limitations of CDC at high luminosity.
  - Only 70% efficiency in conservative scenario.
  - Particle-Id performance not yet evaluated.
- Investigated solutions:
  - Full silicon tracking?
  - TPC + extension of silicon layers up to 44 cm?
  - Timing layer (~30 ps) for particle-Id between tracker & TOP?
- R&D to explore CMOS MAPS for tracking:
  - Specs ~ other tracker projects: ALICE-3, LHCb, FCC-ee.
- ECFA-DRD3: common pixel matrix achievable.
  - With two runs (2025, 2027) in TPSCo 65 nm.
  - Open questions:
    - Stitching (~100 cm^2) for easy integration over large area.
    - Combined with high timing resolution.



Belle II

Human Resources involvement

VTX activities at IN2P3

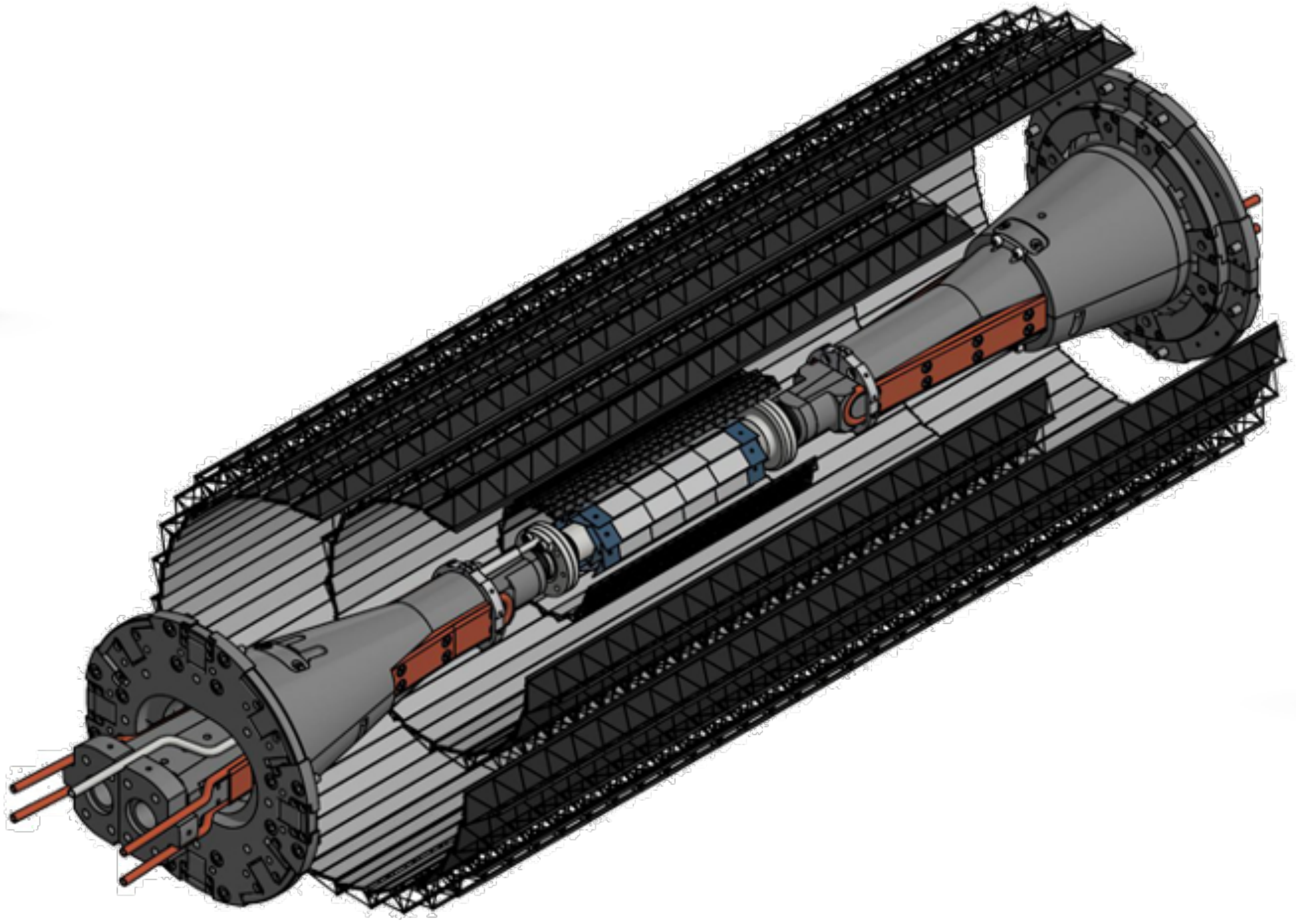
Reconstruction, performance
- **All**

Sensor
- CPPM, **IPHC**
- Leader of OBELIX design

iVTX, oVTX concepts
- CPPM, IJCLab, **IPHC**
- Contribution

Thermo-mechanics
- IJCLab
- Key partner for beam-pipe w/ KEK

Electronic system



HLT
- IJCLab
- Contribution

DAQ
- IJCLab
- Provider of boards chosen by Belle II

Integration, assembly
- CPPM, IJCLab, **IPHC**
- Contribution

Installation and operation
- **All**

Online & offline SW
- **IPHC**
- Contribution

Belle II related activities at IPHC

Description
design of OBELIX-1 and OBELIX-2
characterisation of individual sensors
probe testing of OBELIX-2 sensors
assembly of oVTX detection modules
contribute to the VTX online software
Installation and commissioning at KEK
design for Belle-III
Test for Belle-III

- OBELIX-1: leading group, sensor integration, matrix design, verification
- OBELIX-2: similar arrangement expected, to be decided during OBELIX-1 tests

Expertise with 180 nm process

Design activities — Belle II group

- TJ-Monopix-2, OBELIX-1, OBELIX-2
- Sensor bonding on test-boards provided by patterns
- Characterisation with lab set
- Analysis of data from beam tests organised by partners

Test activities / µ-Tech activities — Belle II group

- Validation of 500-1000 bare sensors in 1 year (with other sites)
- Requires a new probe-test station

µ-Tech activities

- Production of detection modules for oVTX (with other sites)
- Bonding of 400-600 sensors on flex-cables in 1 year (procedure not yet defined)

µ-Tech activities / Belle II group

Belle II group / Test activities

Continuation of activities on current SVD

Within ECFA-DRD3/7

- Specific interest in matrix read-out design, pixel with gain
- Tests limited to lab characterisation & to participation to test beam

Design activities / Test activities — Belle II group

Schedule of VTX activities at C4Pi platform

Description	2023		2024		2025		2026		2027	
	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec
design of OBELIX-1 and OBELIX-2	Design 3 FTE		Design 4 FTE							
characterisation of individual sensors				**B2** + Test 0.5 FTE						
probe testing of OBELIX-2 sensors					µ-Tech 0.5 FTE					
assembly of oVTX detection modules						µ-Tech 1 FTE				
contribute to the VTX online software					**B2** + Test ~0.8 FTE					
Installation and commissioning at KEK								**B2** + Test 0.5 FTE + µTech 0.5 FTE		
design for Belle-III					Design 1-4 FTE					
Test for Belle-III							**B2** + Test 0.5 FTE			

Design activities

µ-Tech activities

Test activities

Conclusion on the Belle II VTX upgrade

- **VTX upgrade required to achieve Belle II physics programme.**
- **Strengthens IPHC position in Belle II.**
- **Key role of IPHC expertise on CMOS.**
- **Belle2-IPHC proposal shaped to fit w.r.t. other IPHC projects relying on C4Pi.**
- **Unique opportunity:**
  - **To maintain expertise of Test and μ-Tech teams at IPHC in coming years,**
  - **To gain expertise on operating a CMOS-based vertex detector at an e^+e^- collider.**


Additional material